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Abstract

This is a final report on the research carried out under the ARO contract DAAG29-85-K-0098 from April 5, 1985 through April 14, 1989. It describes briefly three accomplishments in the area of resonant tunneling through double-barrier devices made of GaAs/$Al_xGa_{1-x}As$ heterostructures. They are: (1) the first experimental demonstration of the importance of many-electron effect in transport through such devices, (2) a self-consistent calculation to take into account the space charge effect and thus to extract spectroscopic information from the experimentally measured I-V characteristics, and (3) the first observation of an intrinsic electrical bistability.

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ELECTRON TRANSPORT IN HETEROJUNCTION SUPERLATTICES

FINAL REPORT

D.C. Tsui

August 1, 1989

U.S. ARMY RESEARCH OFFICE

Contract DAAG29-85-K-0098

Princeton University

Department of Electrical Engineering

Princeton, NJ 08544

Electron transport in heterojunction superlattices

1. Introduction

This research program was started in 1985. It was designed to investigate the charge transport properties of $GaAs/Al_xGa_{1-x}As$ and $In_xGa_{1-x}As/InP$ heterojunction superlattices. The emphasis at the start was on the physics of the electronic processes in such systems and our initial effort was on charge transport through double-barrier resonant tunneling (RT) structures, which are the simplest of semiconductor heterostructures for exploring the basic physics underlying transport in superlattices. We have made several accomplishments in the last two years: (1) a first experimental demonstration of the importance of many-electron effect in transport through such RT devices, (2) a self-consistent calculation to take into account of the space charge effect and thus to extract spectroscopic information from the experimentally measured current-voltage (I-V) characteristics, and (3) the first observation of an intrinsic electrical bistability. In this report, I briefly review these accomplishments and list all publications of work carried out under this contract. More detailed descriptions of the experiments, calculations, and results can be found in these publications.

2. Space charge effect in resonant tunneling structures

Since tunneling is a wave-mechanical phenomenon, resonant tunneling is often described as an electronic analog of the optical Fabry-Perot cavity. Such optical analogies, though conceptually simple and elegant, can often make us overlook some fundamental physics involved in the basic electronic processes. In this case, since the electrons are charged, a resonant build-up of the wave amplitude in the quantum well will give rise to an appreciable charge density in the well. This space charge build-up in the well will change the electrostatics of the problem and alter the voltage distribution across each tunnel barrier. As a result, the energy Δ, (see Fig. 1(a)) separating the Fermi energy in the emitter electrode and the resonant level in the well will not be simply proportional to the applied bias and it is not possible to obtain spectroscopic information directly from the I-V characteristic. We have demonstrated explicitly the importance of this space charge effect by using magneto-tunneling measurements and have formulated a self-consistent calculation to take its effect, as well as those arising from the two electrodes, into account. The solution of this self-consistency problem has made it possible to obtain from the I-V characteristic the relevant energy levels of the tunneling structure.

3. Intrinsic bistability in resonant tunneling structures.

The space charge build-up in the well leads to intrinsic bistability in resonant tunneling (RT) structures: for some range of bias near the peak voltage V_p an RT device can be in either a high current state or a low current state depending on the direction of the biasing voltage ramp. As an RT device is biased beyond the tunneling threshold and tunneling current begins to flow, with the current proportional to the energy Δ in Fig. 1(a), and the transmission coefficient of the emitter barrier, charge is dynamically stored in the well. This charge density, which to first order is proportional to the current, affects the potential distribution over the device, screening the emitter barrier. The electric field in the collector barrier becomes appreciably greater than in the emitter barrier. Hence, if at some fixed bias the current were to increase, the associated increase in the charge density in the well would increase the electric field in the collector barrier and consequently reduce Δ, as well as enhance the emitter barrier. These two effects, in turn, would reduce the current. The electrostatic feedback mechanism is thus complete.

In a certain range of bias the electrostatic feedback can produce two stable current states at the same applied bias. A typical bistable I-V curve of an RT device is shown in Fig. 1(b). As described earlier, resonant current flows through the device as long as the resonant subband in the well remains above the bottom of the conduction band (that is $\Delta \leq E_f$). When the applied bias is ramped up towards V_p the resonant current and the charge density in the well are both high, effectively screening the emitter and maintaining the resonant subband above E_c. On the other hand, when the applied bias is ramped down towards V_p from the current valley range, resonant tunneling is forbidden by conservation of transverse momentum. Both the current and the charge density in the well are low, the emitter barrier is not screened, and consequently Δ is larger. Thus, at some bias slightly below V_p two stable potential distributions are possible, shown schematically in Fig. 1(a): one, drawn with solid lines, is with high current, high charge density in the well, and the resonant subband above the bottom of the conduction band; the other, drawn with dashed lines, is low current and low charge density in the well, and the resonant subband below the conduction band.

Since intrinsic bistability is produced by electrostatic feedback of the space charge dynamically stored in the well of an RT device, the effect can be enhanced by designing an asymmetric structure, with one barrier appreciably larger than the other. In the appropriate bias polarity the lower emitter barrier keeps the current density reasonably large, while the higher collector barrier enhances charge storage in the well. In the other bias polarity, the barrier asymmetry has the opposite effect: peak current density is low, little charge is stored in the well, and no bistability can occur in the I-V curve.

The hysteretic shape of the I-V curve alone is insufficient evidence for the existence of intrinsic bistability, as either large series resistance or biasing circuit oscillation could ostensibly produce a similar I-V characteristic. In this regard, the design of high-impedance RT devices (see I-V curve in Fig. 1(b)) and good Ohmic contacting procedures are clearly essential, suppressing series resistance effects and limiting the maximum oscillation frequency on the RT device. An external capacitor installed close to the device can further stabilize the circuit. However, for conclusive proof of intrinsic bistability we have performed extensive magnetotunneling measurements on bistable RT devices. A magnetic field parallel to the tunneling direction induces Landau quantization in both the emitter and the well of an RT device. In parallel field the transverse momentum states are collected into Landau levels and consequently the I-V curve comes into resonance when Δ changes by the Landau separation $\hbar\omega_c$. As described above, these changes in the energy Δ are self-consistently translated into bias spacing between magneto-tunneling features. When the charge density in the well is high, the bias spacing between magnetotunneling features becomes large due to emitter screening. Representative traces of magnetotunneling conductance in a constant parallel filed are shown in Fig. 2. The difference in bias spacing between the high and low current states in the bistable range, due to different charge densities in the well is further evidence for the intrinsic bistability. In the low current state the bias spacing is lower by a factor of ~ 6, in agreement with self-consistent numerical calculations. Thus we have experimentally confirmed the existence of intrinsic bistability in resonant tunneling structures.

4. Phonon side-band and impurity-assisted tunneling.

The formulation of a self-consistent calculation to properly account for the space charge effect has made it possible for us to obtain spectroscopic information from the observed fine structures in the I-V characteristic. It allows us to translate the applied voltage into Δ and to identify through the energetics the underlying electronic processes. We have identified that the weak structure in the valley region of the I-V is indeed a phonon side-band due to inelastic tunneling of an electron through the first barrier with the emission of a longitudinal optical (LO) phonon. In addition, by using magneto-tunneling and also from the magneto-oscillatory conductance, we have identified the current component due to impurity-assisted tunneling, which does not conserve momentum parallel to the surface. Thus, we have been able to quantitatively account for the experimentally measured I-V and identified the underlying electronic processes without addressing the problem of phase coherence through the structure. We believe that the dominant phase breaking mechanism is the electron-electron interaction in the well and we are currently investigating this aspect of the problem.

Publications

A. Refereed Journals:

A1. V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Observation of intrinsic bistability in resonant tunneling structures," Phys. Rev. Lett. **58**, 1256 (1987).

A2. V.J. Goldman, D.C. Tsui and J.E. Cunningham, and W.T. Tsang, "Transport in double barrier resonant tunneling structures," J. Appl. Phys. **61**, 2693 (1987).

A3. V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Resonant tunneling in magnetic fields: evidence for charge build-up," Phys. Rev. B **35**, 9387 (1987).

A4. V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Evidence for phonon-emission-assisted tunneling in double-barrier heterostructures," Phys. Rev. B **36**, Nov. 15, 1987.

A5. A. Zaslavsky, V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Resonant tunneling and intrinsic bistability in asymmetric double-barrier heterostructures," Appl. Phys. Lett. **53**, 1408 (1988).

B. Conference Proceedings

B1. V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Charge transport and intrinsic bistability in resonant tunneling structures," Proc. of the 1987 International Conference on Modulated Semiconductor Structures, J. de Physique C **5**, 463 (1987).

B2. V.J. Goldman, D.C. Tsui and J.E. Cunningham, "Breakdown of coherence in resonant tunneling through double barrier heterostructures," Proc. of the 1988 International Conference on Modulated Semiconductor Structures, Solid-state Electronics, **31**. 731 (1988).

FIGURE CAPTIONS

Fig. 1. (a) Schematic conduction band diagram of the two current states that can exist at the same applied bias V_{app} in a bistable resonant tunneling device. In the high-current state (solid lines) there is significant charge storage in the well, which screens the emitter barrier and keeps the resonant subband E_0 lined up with the three-dimensional electronic states in the emitter. In the low-current state (dashed lines) there is little charge storage and the subband E_0 drops below the bottom of the three-dimensional emitter conduction band. (b) Representative I-V curve of a high-quality bistable resonant tunneling device at T = 4.2 K.

FIG. 2. Conductance of a resonant tunneling device at three values of parallel magnetic field: B = 0, 4.0, and 6.0 T. The existence of two states with different charge densities stored in the well is clear from the spacing of the magnetotunneling features.

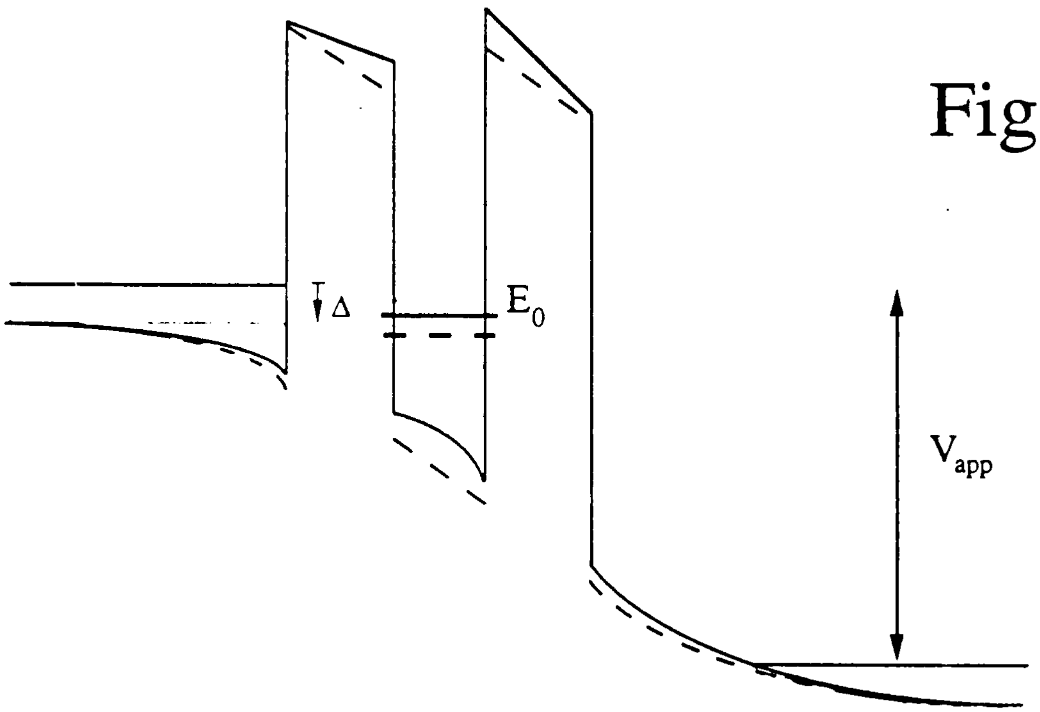

Fig. 1 (a)

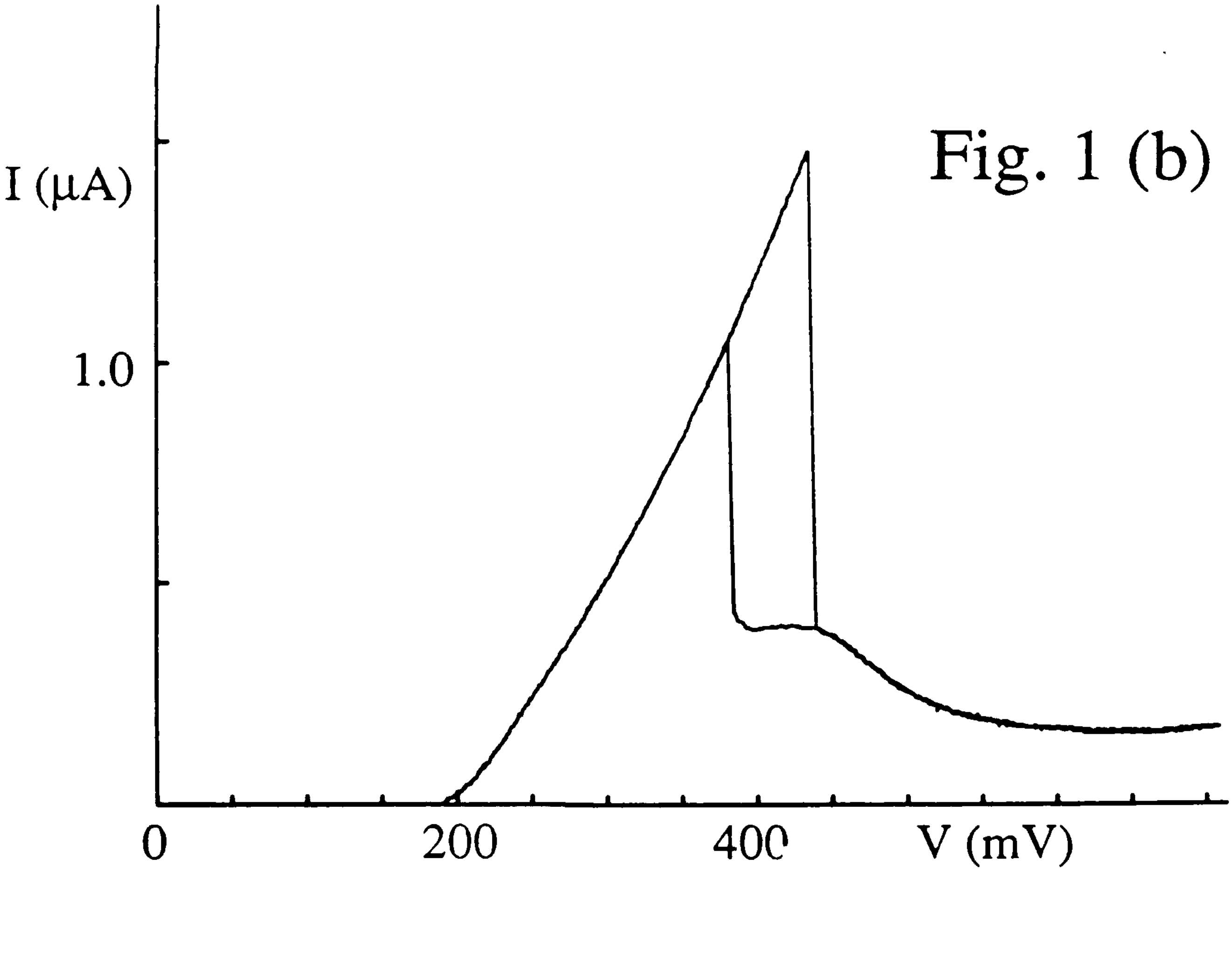

Fig. 1 (b)

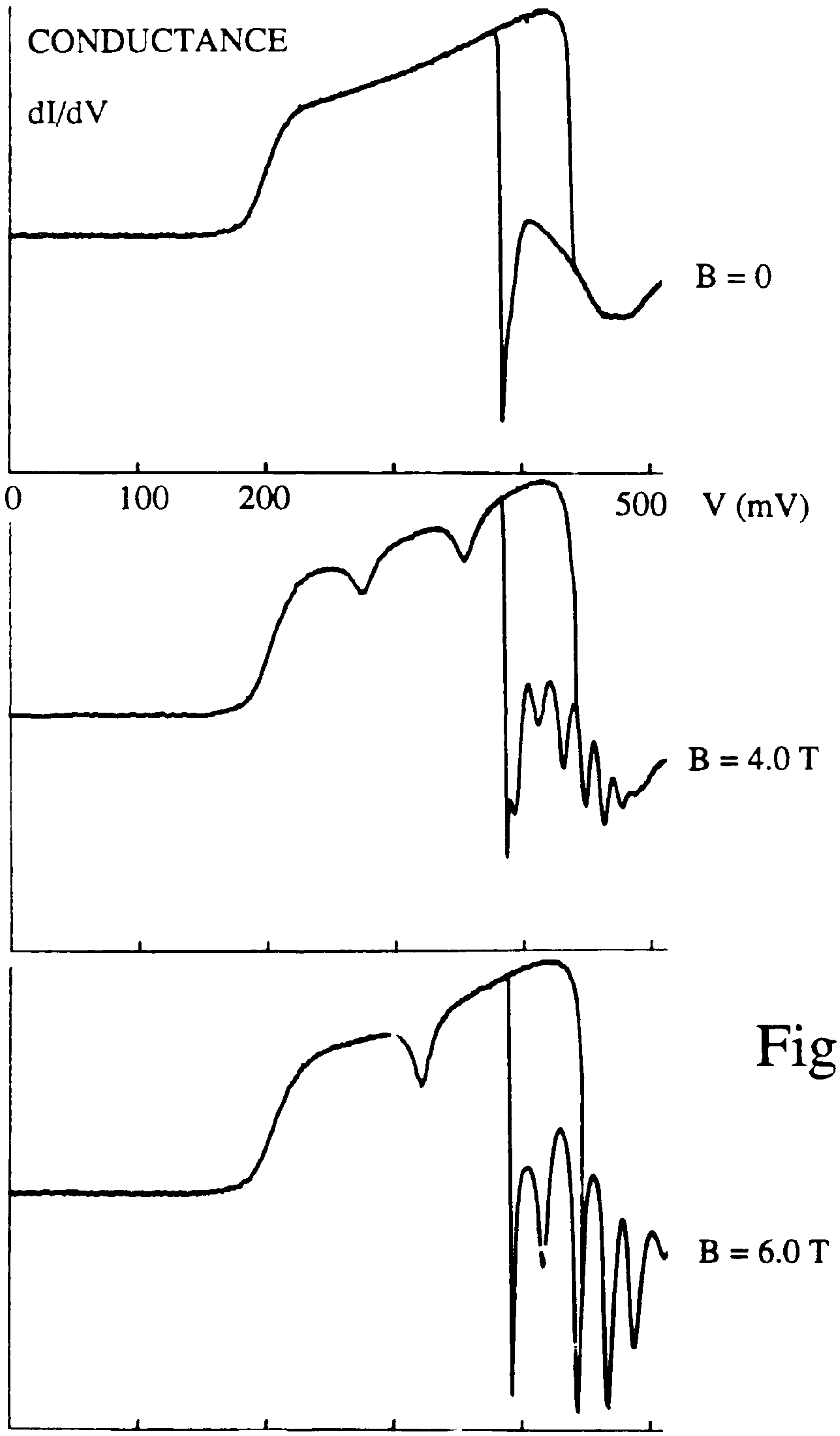

Fig. 2

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